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# Viability of CCS: A broad-based assessment for Malaysia

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ABSTRACT

Climate change is fast becoming the major environmental and energy concern worldwide. There is a major dilemma between the continued reliance on fossil fuel for our energy supply and the pressing need to address the problem of greenhouse gas (GHG) emissions from combustion process. This paper reviews the potential for carbon capture and storage (CCS) as a part of the climate change mitigation strategy for the Malaysian electricity sector using a technology assessment framework. The nation's historical trend of high reliance on fossil fuel for its electricity sector makes it a prime candidate for CCS adoption. The suitability and practicality of the technology was reviewed from a broad perspective with consideration of Malaysia-specific conditions. It is apparent from this assessment that CCS has the potential to play an important role in Malaysia's climate change mitigation strategy provided that key criteria are fulfilled.



**Contents**



## 1. Introduction

Climate change currently ranks as one of humanity's greatest challenge [1,2] in view of the potential catastrophic impact upon the world and the enormous global effort required to mitigate it. There have been increasing awareness on the importance of addressing climate change and in 2007; the Nobel Peace Prize was

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dedicated to individuals and groups who have worked to address the issue.

Combustion of fossil fuel has been identified as the leading source of $CO_2$ emissions into the atmosphere which is the key driver for anthropogenic climate change. In order to reduce the emissions of $CO_2$ different technology options have been proposed and explored in order to achieve a sustainable low carbon energy society. There is no clear single technology option available that could solve the emissions issue of our energy needs and most likely a portfolio of technology solutions would be required in order to prevent dangerous anthropogenic interference with the climate system [3–6].

Uncertainty and lack of clear technological solution for clean, reliable and accessible energy with low emissions into the atmosphere have compounded the complexities of efforts needed to stop climate change [7]. There have been intense competitions for funding critical towards the research, development and deployment of these mitigation technologies. For this reason, proper screening and assessment for the selection of possible technological propositions is required. Carbon capture and storage (CCS) has been projected as a potential solution for minimizing the emissions of $CO_2$ from power plants, industries and other large $CO_2$ emission point sources but doubts on its suitability still remains. Malaysia, as with many other countries with a high reliance on fossil fuel for its electricity (see e.g. [8]), are potential adopters of the technology. This paper seeks to examine CCS from a broad perspective in order to assess its suitability for inclusion into Malaysia's portfolio of greenhouse gas (GHG) mitigation options.

## 2. Methodology

Technology assessment is an important instrument for the review of possible technological solutions. It has been a growing field of technology management study and receives considerable attention by researchers in the public and private domains. The concept was first pioneered in the 1960s in the United States through the establishment of the Office of Technology Assessment (OTA) to fulfill the U.S. Congress policy needs. Technology assessment has been classically defined as "a class of policy studies to systematically examine the effects on society that may occur when a technology is introduced, extended or modified" [9].

There are many different approaches for technology assessment (see e.g. [10–13]), but this paper utilizes a framework based upon earlier works by MacGill et al. [14–16]. It is essentially a risk-based technology assessment framework for GHG mitigation technologies and serves as a screening tool for the suitability of the technology for its intended purpose. Of the assessment methods available, this particular framework was selected due to its ability to assess the specific mitigation technology from a broad perspective. Technologies are reviewed from a number of different aspects which in turn provides a valuable presentation on the potential and impact of a proposed technology introduction. In addition to the above framework, this paper also covers the evaluation of the technology readiness level (TRL) of CCS in order to obtain a comprehensible indicator on the technology maturity. The TRL concept was pioneered by the National Aeronautics and Space Administration (NASA) for the evaluation of its space shuttle programs and later was adapted by the U.S. Department of Energy (DOE) for the assessment of its major research programs. The concept has since been adopted by other agencies and organizations worldwide for the assessment of a wide range of technologies. The TRL evaluation introduced further complements the framework technical status assessment of the framework and thus provides a comprehensive indicator on the technology readiness. Fig. 1 provides a schematic overview of the overall framework utilize for this study.

## 3. CCS as a mitigation technology option

### *3.1. Technical status*

CCS is a concept made up of three major technology components; the capture, the transport and the storage of the $CO_2$. All of these components are essential for the effectiveness of CCS.

#### *3.1.1. Capture*

Capture of $CO_2$ for CCS can be achieved using one of the three main methods being developed. Capture can be done via post-combustion capture, pre-combustion capture or oxyfuel combustion [17].

Of the three capture methods, post-combustion capture utilizing amine scrubbing is the leading solution for effective capture of $CO_2$ from flue gas streams. Currently there are already established industrial applications of amine scrubbing for acquiring pure stream of $CO_2$ for commercial purpose. The most notable project on capturing of $CO_2$ for climate change mitigation purpose in Sleipner, Norway also adopted the amine scrubbing method for $CO_2$ separa-

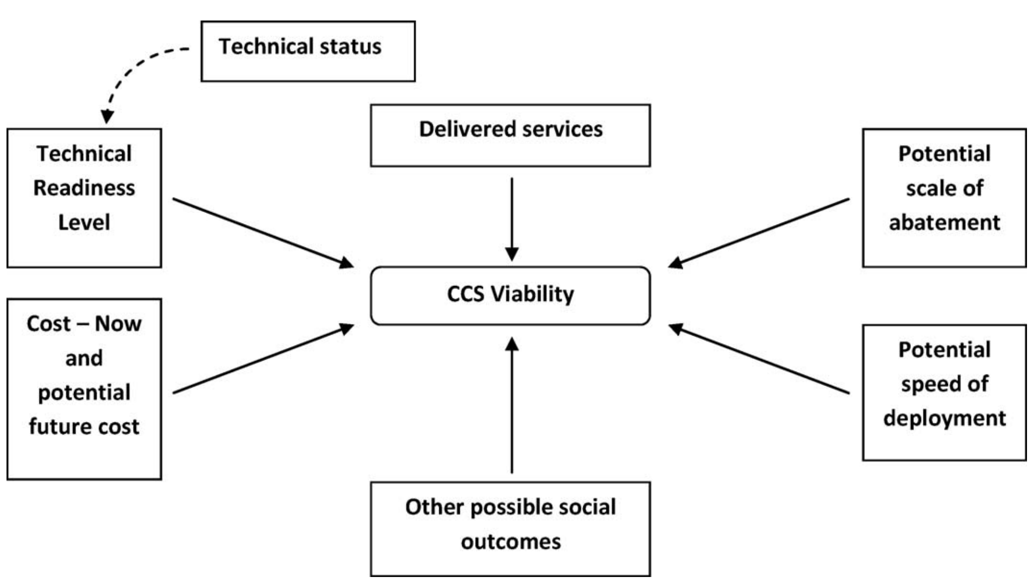


**Fig. 1.** Schematic representation of a risk-based technology assessment framework for CCS.

tion [18]. However, the low concentration of $CO_2$ in power plant flue gas and the sheer volume of gas emitted provide additional challenges for the use of post-combustion capture. The current process still requires much effort and energy. Recent evidence suggests that energy penalty incurred for post-combustion capture will range between 22 and 29% [19]. These findings were derived based on the current known absorbents and processes. Further research is ongoing in establishing the best mix of chemicals for absorbents with better suited properties for the selective separation of $CO_2$. This in return might translate into better capture performance and lower energy/cost from the process. Some reviews of the recent advances and the future for post-combustion capture can be found in [20–23]. Prior TRL assessment on the post-combustion capture had rated the technology to be in a range of between 2 and 7, depending on the exact configuration employed [24,25].

In order to overcome the hassle of dealing with the huge volume of flue gas with very low $CO_2$ concentration, there have been efforts to capture $CO_2$ from power plants prior to the combustion process. The pre-combustion capture method for $CO_2$ is best suited for integration with the integrated gasification combined cycle (IGCC) power plants. In an IGCC power plant, coal or other suitable feed stock are gasified (partially combusted) to produce syngas which is a mixture of hydrogen and $CO_2$. The $CO_2$ can be separated while the hydrogen is used for power generation. Pre-combustion capture using physical solvents can be introduced for IGCC systems due to the high partial pressure of $CO_2$ in syngas. This will allow a less costly process for the separation of $CO_2$. Despite the potential, there are still no operating IGCC systems with $CO_2$ capture till date. Moreover, the deployment of IGCC systems worldwide has not been so successful. By 2004, there were only limited IGCC systems in operations with the systems contributing only a mere 4 GWe of the world total electricity generation [26]. Proponents of IGCC with CCS, however, believe that IGCC with CCS would be a viable clean coal technology providing the opportunity for the continued extraction of energy from the cheap and abundant source of coal without the harmful emissions to the environment. It has also the potential for the lowest cost for capture $/t$CO_2$. The Electric Power Research Institute (EPRI) reports that the TRL for pre-combustion capture technology is rated at 9, which is the technology readiness level for mass deployment [27,28]. However, the challenge would be first to establish the IGCC technology and to overcome the high capital cost for the plant, to increase reliability, availability and to lower the cost of electricity from this generation technology. Once achieved, IGCC with pre-combustion capture would be an attractive technology for deployment.

A different approach to minimize the amount of flue gas for $CO_2$ capture is through the method of oxyfuel combustion power plants. The concept directly addresses the need to separate $N_2$ from $CO_2$ in combustion flue gas. In an oxyfuel combustion power plant, high purity $O_2$ is used for combustion. As an outcome from this change of feed gas, the flue gas will now be made up almost entirely by $CO_2$ and water vapor, which will be readily available for capture [17]. Positive impact from this change includes a significantly lower volume of flue gas for treatment, the ability to separate $CO_2$ simply by drying up the water vapor composition and minimize formation of NOx. Conversely, the need to produce pure $O_2$ for combustion instead of just using atmospheric filtered air increases the overall cost for electricity generation. Additional capital expenditures are required for the installation of the key components for oxyfuel combustion plants namely the air separation units (ASU), the flue gas recycle system and the $CO_2$ purification and compression system. Moreover, there is a considerable energy penalty cost from the use of the ASU. A number of studies estimated that the ASU consumes between 0.200 and 0.275 kilowatt-hour electric (kWhe) which is equivalent to between 20 and 30% of the plant electricity output [17,29,30]. The oxyfuel combustion concept is still far from being ready for large scale deployment. There has not been any commercial version of the technology in operation as of yet. The technical readiness of the technology as rated by the research group from Imperial College London is at 5, based on oxyfuel combustion with cryogenic air separation [25].

### 3.1.2. Transport

The likelihood that the large emission source and storage locations might differ necessitates an effective and reliable system for transfer of the captured $CO_2$. Technology for transport of $CO_2$ is perhaps the most established when compared with the capture and storage part of CCS. There are a number of options available for the movement of a large amount of gas across great distances, differing geographical terrain and population settings. Options for the transport of $CO_2$ overland include trucks, railways and pipelines. For large distances and quantity of $CO_2$ which is expected from a commercial scale CCS project, pipeline transportation will be the preferred option for transportation across distances on land. For example, a 500 MW power plant will on average produce 3 metric tonnes (Mt) of captured $CO_2$ per year. Therefore, transportation via pipelines in such cases would make economic sense [31–33].

The transport of $CO_2$, as a matter of fact, can be analogous to the transportation of other hydrocarbons. Pipelines have been in commercial applications for the transfer of natural gas, oil, water and industrial substances among others over land or sea without much complication. Furthermore, there has also been some experience with industrial scale transportation of $CO_2$ by pipelines. In the US, there has been more than 2500 km of pipelines with a transport capacity of up to 40 Mt$CO_2$ per year established for the supply of $CO_2$ for EOR purposes [17,34,35]. For offshore storage locations, transportation options available include pipeline transportation and ocean tankers. Liquefied natural gas (LNG) and other petroleum gasses have already been transported using ocean tankers. Therefore, $CO_2$ can also be successfully transferred through tankers. There has also been a limited number of ships dedicated for $CO_2$ transport used for the shipment of liquefied food grade $CO_2$ from source points to consumer regions [17]. Further details regarding the use of transport ships for $CO_2$ transfer can be found in [36,37].

Transport of large amounts of $CO_2$ definitely needs to be well-considered and planned. However, transport of $CO_2$ should be a relatively simple consideration in an overall CCS theme as there are already ample experiences from the transportation of mass amount of hydrocarbon over distances. Transport can be considered less challenging relative to capture and storage of $CO_2$. The Global CCS Institute report on CCS readiness rates the TRL for pipeline transportation to be at 9, which correspond to a technology which is ready for full scale commercial deployment [38].

### 3.1.3. Storage

There are a number of potential storage options in deep geological formations. The leading options include deep saline aquifers, unminable coal seams, abandoned oil and gas reservoirs and also storage through enhanced hydrocarbon recovery. Geological storage is accomplished by injecting the compressed stream of $CO_2$ into these geological formations which are mostly located within sedimentary basins. The technology for injecting $CO_2$ into the ground for storage is already well established and is reliable [39,40]. However, more importantly these storage options should fulfill the following key criteria for $CO_2$ storage [39]:

- "The storage period should be prolonged, preferably hundreds to thousands of years.

**Table 1**
Summary of TRL scores for CCS technology components.

| Component | TRL |
|---|---|
| Capture | |
| Post-combustion capture | 2–7 |
| Pre-combustion capture | 9 |
| Oxyfuel combustion | 5 |
| Transport | 9 |
| Storage | 9 |

- The cost of storage, including the cost of transportation from the source to the storage site, should be minimized.
- The risk of accidents should be eliminated.
- The environmental impact should be minimal.
- The storage method should not violate any national or international laws and regulations."

The use of these storage locations for long term gas storage has already been proven by numerous commercial experiences with the injection of gasses into underground geological formations:

- Storage of natural gas for seasonal demand and delivery [41].
- Injection of acid gas into geological formations for storage [42].
- Enhanced oil recovery (EOR) with $CO_2$ [43].

These prior experiences which are close or analogous to the storage of $CO_2$ provide confidence in the ability of geological mediums to store gas over extended periods of time. Therefore, the identification and verification of suitable storage sites nearest to the emission sources are important steps in the deployment of CCS initiatives.

#### 3.1.4. CCS as an integrated system

The experience with CCS as a fully integrated system for $CO_2$ mitigation at this stage is still rather limited. Other than a few large scale demonstration projects, large scale CCS has yet to be deployed on a commercial basis. Therefore, CCS as a complete system has yet to fulfill TRL level 9 (as per the U.S. DOE TRL definition); where the actual system has yet to be operated over the full range of excepted conditions on a commercial basis. The overall components that make up the overall CCS technology are presently in various stages of TRL as summarized from the literatures in Table 1.

Therefore the ongoing and planned large scale demonstration of CCS systems constitutes an important step as it would help to establish the technical readiness of the CCS concept and is a much needed learning phase prior to the commercial roll out of CCS. Without success from these pioneer projects, it would be risky and almost impossible to roll out commercial CCS initiatives.

### 3.2. Delivered services

The main benefit from the deployment of CCS is the ability to prevent the release of up to 90% of $CO_2$ emissions into the atmosphere. Unlike renewable energy, the use of CCS does not eliminate the formation of $CO_2$ but rather prevents it from getting into the atmosphere. Nonetheless, the use of the technology might provide the opportunity to achieve a $CO_2$ emission scenario of between 10 and 20% from the business as usual scenario (conventional fossil power plant without CCS). There has been an increasing opinion that contribution from CCS together with other mitigation efforts would be required in order to prevent the catastrophic damages of climate change [5,17,44]. It is also envisioned that the cost of mitigation will be lower with the inclusion of CCS. The Stern report [5] has estimated the impact of climate change might cost 5–20% of the world GDP whereas the actions needed for mitigation might just be about 1% of the world GDP if technologies like CCS are included.

As CCS is integrated into existing power plant technologies, the electricity generation and distribution infrastructure, for the most part, will remain unchanged. Power plants and other large utility infrastructure had taken a substantial number of years to be developed and constructed with a planned long service life. CCS provides the opportunity for the continued usage of these facilities without radical changes thus allowing a more gradual transition towards future sustainable renewable energy systems. Existing sites and in some cases existing power plants can be retrofitted with CCS, allowing emission reduction from the current fleet of generation plants. This will enable an almost immediate action on cutting carbon emissions. The knowledge and experience build up from the years of experience in operating fossil based power plants would also still be applicable for the case of introducing CCS. Expertise and skilled professionals would require time to be nurtured. CCS provides the opportunity for the continued operations of these power plants while building up the next generations of renewable based power supply.

The introduction of CCS also provides an opportunity for the continued usage of coal and other fossil based fuels for energy in a carbon constrained world. Coal and other fossil fuels have been the main source of energy for centuries but the carbon emissions from fossil fuel energy have now become a major concern. CCS provides a possible path towards minimizing the emissions from the combustion these reliable energy sources. The world has historically had been dependent on fossil fuel for energy, with much innovation and development already achieved in the field. Much has been invested in the infrastructure that will enable the extraction; transport and conversion of fossil fuel into energy supply such as electricity. CCS could potentially allow the continued usage of these infrastructures while awaiting the availability of more sustainable energy source such as renewable based energy. The availability of CCS also facilitates the transition pace into sustainable energy sources. Proper planning and organization can be done. The fossil fuel energy infrastructure took centuries to be developed and construct. Therefore, it would not be realistic to expect non-fossil based energy sources to be available within a matter of years. From an energy security perspective, CCS enables the inclusion of fossil fuel into the generation mix in a carbon constrained environment. There is an option to make use of the different types of fossil fuels for energy even though there is a cap on emissions.

At the moment, there might not be many industrial applications for $CO_2$. For the petroleum exploration, a huge quantity of $CO_2$ is used for EOR purposes. However, it is unlikely that EOR itself would be able to consume all the $CO_2$ captured for climate change mitigation purposes. Continued technology development and advancement could potentially yield further useful application for $CO_2$. Therefore, the CCS stored $CO_2$ might become useful in the future when new forms of applications are established.

### 3.3. Cost—now and potential future cost

The cost of CCS has been a notable topic of interest as it remains one of the major barriers that need to be addressed in order to fully deploy the technology. There have been a number of prior studies undertaken to estimate the potential cost range of CCS power plants and the cost per ton of $CO_2$ captured from power plants. However, it is noted that CCS cost studies are implemented with a host of different cost assumptions that will dramatically affect the outcomes [45]. There are a number of factors that affect the cost of CCS (e.g. see [46]).

Moreover, different power plant technologies have distinct capture requirements and therefore, there is a quite dissimilar estimated cost figure for different power plant technologies with CCS. Even the different types of fuel sources have an impact on CCS cost estimates. It has also been featured that the effects on projected

**Table 2**
Prior studies capture cost estimates (cost in USD/ton $CO_2$).

| Source | Initial cost | Future cost |
|---|---|---|
| Davids and Herzog [50] | | |
| Coal | 35.1 | 26.7 |
| IGCC | 21.5 | 15.8 |
| Natural gas | 42.6 | 36.9 |
| Rubin et al. [19] | | |
| Coal | 29–44 | |
| IGCC | 11–32 | |
| Natural gas | 28–57 | |
| Davison [51] | | |
| Coal | 30–33 | |
| IGCC | 20–33 | |
| Natural gas | 28–57 | |
| Rubin et al. [45] | | |
| Coal | 29–51 | |
| IGCC | 13–37 | |
| Natural gas | 37–74 | |
| McKinsey [48] | | |
| Coal/gas | 33.75–43.2 | 24.3–33.75 |

cost of CCS due to differing fuel prices and quality, plant utilization rates and size, financing and other operating assumptions [45].

Transportation and storage cost is also an important component of the overall total CCS cost. There had been tendencies by prior studies to focus more exclusively on $CO_2$ capture costs and do not include the costs of transport and storage [45]. This is in line with the fact that the majority of the overall CCS cost is related to the capture of $CO_2$ [47]. Despite that, the cost for transport and storage must still be considered and address for the implementation of CCS. The distance between points of capture and storage, the geographical terrain involved, and the mode of transport selected has an impact on the cost involved [32,48,49]. For specific cases such as storage through EOR, the additional income from EOR might even help to further reduce the cost of CCS. Actual cost for transportation and storage would therefore differ depending on the actual situation.

It is difficult to have a definite figure on the cost for CCS implementation. Nevertheless, the estimated range of cost of capture per ton of $CO_2$ still provides a guide on the probable magnitude of the cost. A range of estimated costs of prior studies on $CO_2$ capture, transport and storage are illustrated in Tables 2 and 3.

There had also been optimistic views that the cost for CCS would subsequently be reduced in the future due to improved technology and process performance. It is a formidable challenge to accurately predict these potential cost reductions. However, some technologies analogous to CCS can provide guidance on the possibility for cheaper CCS technology. Historically, emission control system costs tend to reduce with the increased deployment of the technology and improvement of its performance. A technology concept close to the capture of $CO_2$ is the flue gas desulphurization technology (FGD) which was introduced into service at commercial coal power plants in the late 1960s for the control of $SO_2$, the cause of acid rain in the United States. In the initial stage of the introduction, it was also marred with the issue of high costs. However, a clear trend in the reduction of capital cost of FGD units was subsequently observed with further increase in the capacity installed and improvement in process efficiency (see [52]).

Scores of new product and innovation costs have decreased over time due to increased experience with production. There have been a number of studies detailing the impact of technology learning on technology cost. McDonald and Schrattenholzer had also identified the usefulness of learning rates (or learning rate distributions) of energy conversion technologies for energy models [53]. Specifically, for CCS technology, Rubin and colleagues made use of experience curves to estimate the future cost of CCS [47,54].

**Table 4**
Summary of $CO_2$ storage capacity estimates for deep saline formations, EOR, and ECBM.

| Formation | Worldwide storage (Gt $CO_2$) |
|---|---|
| Deep saline aquifers | $10^3$ to $10^4$ |
| EOR and depleted oil and gas fields | $10^3$ |
| ECBM | $10^1$ to $10^2$ |

*Source*: Adapted from Ref. [58].

### 3.4. Potential scale of abatement

The potential scale of abatement is highly dependent on the capability of the technology and the availability of quality storage capacity. The previous section already covered the technical readiness and potential of the technology; therefore, the other limiting factor for the scale of abatement would be the available storage capacity. There have been a number of studies into the potential storage on a global, regional and even national basis. The IPCC SRCCS [17] and IEA [55] have noted that although a definitive figure on the total worldwide storage capacity might not be agreed upon; there is general consensus that there is more than enough storage space for $CO_2$ mitigation purposes. Table 4 provides an overview on the potential storage capacity available for CCS. Even based on the most conservative estimate, there are still large enough storage capacities for the purpose of climate change mitigation.

From a capacity perspective, deep saline aquifers offer the most geological storage capacity. Storage through EOR and also other depleted or uneconomical oil fields are also in abundance and constitute as an attractive options to be explored in view of the positive economic offset of cost from the enhanced extraction of petroleum. So far, a number of demonstrations and commercial projects for $CO_2$ geological storage around the world has been established successfully; further details are available from [56]. The experience gained from these early projects on $CO_2$ storage include those in Sleipner, Salah and Weyburn have helped to increase the knowledge and understanding of the science for long term storage of $CO_2$ in geological mediums. With early success and commercial experience for $CO_2$ the storage is thus rated at 9 for technology readiness [57].

### 3.5. Potential speed of deployment

Due to the differing views on the technical readiness, the cost of technology and the lack of clear policy guidelines and pricing on carbon emissions, there is also an unclear estimate on the time-

**Table 3**
Prior studies transport and storage cost estimates (cost in USD/ton $CO_2$).

| Source | Transport | | Storage | | Total | |
|---|---|---|---|---|---|---|
| | Initial | Future | Initial | Future | Initial | Future |
| Rubin et al. [19] | 3.2 | | 5 | | 8.2 | |
| Considering EOR | 3.2 | | −5 | | −1.8 | |
| Rubin et al. [45] | 3.1 | | 5 | | 8.1 | |
| Considering EOR | 3.1 | | −10 | | −6.9 | |
| McKinsey [48] | 5.4–8.1 | 2.7–5.4 | 5.4–16.2 | 2.7–13.5 | 10.8–24.3 | 5.4–18.9 |

**Table 5**
Potential year for CCS commercialization.

| Study | Estimated year for commercialization |
|---|---|
| UK DERR [59] | 2020 |
| The North Sea Basin Task Force [60] | 2020[a]/2030[b] |
| NETL/USDOE [61] | 2020 |
| IEA [62] | 2020 |
| McKinsey & Co. [48] | 2020[a]/2030[b] |

[a] Early commercialization.
[b] Mature commercialization.

lines for the deployment of CCS technologies. However, it is widely believed (refer to Table 5) that CCS would be ready for commercial deployment by 2020.

As of today, there are still no commercial CCS power plants in operation yet. Although, major parts of the technology components (capture, transport and storage) have already been utilized in industrial settings, the integration of the components of technology and scaling up the capacity to handle the large volume of emissions from commercial power plants would be a challenge. Large scale demonstration projects have already begun and the speed of deployment of CCS will depend on the outcome of these pioneer projects. There had been a big push for these demonstration projects to be initiated as these projects provide an opportunity for experience and learning on the implementation process. Knowledge gained is then utilized for further commercial roll out of the technology. A favorable speed of deployment increases the attractiveness of CCS as a mitigation technology, particularly in the scenario where CCS is positioned as a medium term mitigation technology while awaiting the development of a more sustainable and cleaner energy system.

### *3.6. Other possible social outcomes*

The deployment of CCS does also impact other social outcomes. The high cost of CCS would translate into a higher electricity cost for electricity producers and ultimately consumers as well. Energy, especially electricity has become an essential part of society today and the access to affordable and reliable electricity supply constitutes a basic right for all [63,64]. The high cost of CCS might increase the cost of electricity which might lead to a higher electricity tariff for consumers. If viewed from a different perspective, the rise in electricity prices might be a positive move towards encouraging better energy efficiency [64] but again the increase should be kept in check to ensure it does not become an economic burden to lower income consumers.

The risks of local residents' resistance towards CCS projects are another possible scenario to be considered. Public opposition to project siting has been a major concern for the deployment of climate change mitigation technologies (see [65–67]). Lack of information, misconception and fear of the unknown are just some of the potential factors that will alienate public support for these large scale projects.

## 4. The case for CCS in Malaysia

### *4.1. Technical status*

Malaysia currently has limited capabilities in researching and developing cost effective $CO_2$ separation technologies. There have been a limited number of reviews on the potential and technical feasibility for CCS in Malaysia (e.g. see [68,69]). There has been no large scale funded research initiative for CCS in Malaysia and it is likely that the capture technology as with most climate change mitigation technologies would have been developed by industrialized nations [70].

Gibbins and Chalmers has also suggested in their models that the roll out of CCS would first take place in developed nations and then followed by the developing nations [71]. It would be pragmatically easier for the deployment of CCS in Malaysia if the technology has already reached a certain level of maturity and there are already sufficient experiences with a wide scale roll out. Currently, for power plants, there has not been any established local provider of the technology and there has been a tendency for Malaysian companies to form ventures with technology providers from the industrialized nations. It is envisioned that the same approach might be adopted for the deployment of CCS in Malaysia as local firms has the potential to gain sustainable competitive advantages through such ventures [72]. As an example, there has been a major capture and separation $CO_2$ facility in service for urea production in Malaysia [73] which was set up successfully with the participation of the Japanese technology provider.

In terms of transportation for $CO_2$, Malaysia could benefit from its well established oil and gas industry. As the challenge from the transportation of $CO_2$ would likely be similar to that of the transfer of other hydro carbon gasses, Malaysia would be well prepared to support this undertaking. There has already been the layout of 1700 km of pipelines for the purpose of natural gas transmission in peninsular Malaysia [74], even though there has not been any pipeline specific for $CO_2$ transfer. Expertise in these fields could also support the development of $CO_2$ transportation pipelines in the future.

Although there has not been any specific geological storage for $CO_2$ in Malaysia, there have been a number of proposals for it. A notable proposal is the CDM project application (under UNFCC-NM0168) for a mitigation project in Bintulu, Malaysia for the capture of $CO_2$ and $H_2S$ from a natural gas processing facility for storage in deep saline aquifers [75]. There were also numerous plans for the introduction of EOR for Malaysian oil fields [76].

There have also been limited studies on the availability of geological storage for Malaysia [77]. Hence, a more detailed study on the actual potential capacity for geological storage in Malaysia and its surrounding issues would be a key priority in any serious consideration for the deployment of CCS.

### *4.2. Delivered services*

The main advantage of CCS for Malaysia is the capability to address the $CO_2$ emissions from its fossil fuel based power plants. As of 2007, up to 90% of Malaysia's electricity generations still originate from the combustion of fossil fuel [8]. Coal provides 30% of the generation capacity and there are plans to increase this figure. CCS is the most suitable technology to be deployed with conventional thermal power plants for $CO_2$ emission reductions. There had been efforts to increase the contribution from renewable energy in the generation mix, but if a percentage of fossil fuel power plants are to be maintained for energy security and diversification purpose, CCS would be an attractive option to be considered. Therefore, the use of CCS would be a good choice for reducing emissions while awaiting a cleaner, reliable and sustainable energy alternative to fossil fuels.

### *4.3. Cost—now and potential future cost*

The initial deployment cost of CCS technology in Malaysia would be high and comparable to implementation elsewhere. The implementation cost would be lower if;

- CCS has already been widely deployed in industrialized countries and certain maturity in the technology has been achieved.
- For the initial implementation, certain funding is received (e.g. CDM) [78].


**Fig. 2.** Distribution of Malaysia's sedimentary basins [79].

Prior experiences elsewhere of wide scale deployment of the technology would be beneficial for further deployment. Therefore, if the technology was to be implemented at a later stage in Malaysia, lower cost would be expected relative to the first-of-its-kind implementation project cost. However, there tends to be financial assistance available for pioneering project implementation. Financial benefits in the form of financial assistance, subsidy and tax rebates are just some examples of possible policy instruments that would help to offset the high implementation cost.

At the moment, Malaysia as a developing nation still enjoys the benefit of participating and gaining from the Clean Development Mechanism (CDM) incentive. However, this status might change in the near future if Malaysia achieves its aims of becoming a developed nation by 2020.

### *4.4. Potential scale of abatement*

The scale of abatement would depend highly upon the available storage capacity for captured $CO_2$ from large point sources. Prior studies on the potential storage capacity list the possibility of storage in deep saline aquifers in the Malay Basin off the coast of peninsular Malaysia [77]. However, a more comprehensive study would be required to verify the capacity attainable and also to consider other forms of geological storage available, including EOR.

Majority of the existing power plants in Malaysia with high emission rates of $CO_2$ are located in the west coast of Peninsular Malaysia. There would be a possibility that these and future power plant emissions could be piped over for storage within suitable geologic formations in the Malay basin. Penyu basin could also offer additional storage potential for the power plants in the peninsular while the power plants located in the state of Sabah and Sarawak could make good use of their respective offshore sedimentary basins which are suitable for geologic storage of $CO_2$. Fig. 2 illustrates the location of major sedimentary basins around Malaysia.

### *4.5. Potential speed of deployment*

The speed of deployment would likely be in line with the speed of deployment elsewhere. Numerous factors would affect the speed of deployment, including motivations and regulations requirements. Malaysia would be able to deploy first if some form of financial incentive (via mechanisms like CDM or equivalent) and technical assistance are available. There is also the likelihood that once Malaysia signs up to a legally binding emissions target, there would be a bigger demand for the deployment of CCS. Nevertheless, this would still depend on the technical readiness and maturity of the technology from the demonstration and deployment elsewhere.

### *4.6. Other possible social outcomes*

The introduction of CCS would most likely increase the cost of electricity for the producers. There has been a tendency for the utilities to pass on the cost increase to consumers, but utilities tariffs are regulated by the government in Malaysia. Therefore, it would still be within the purview of the legislator to decide if the full cost increase should be passed on to the consumers. A higher utility pricing would help to cultivate energy efficiency practices but the needs of the lower income consumers should also be considered. The industries with high electricity intensity in their operations would also be affected by higher electricity pricing. A higher electricity cost might deter investment from investors of energy intensive activities (e.g. aluminum smelting, pulp and paper, chemical processing).

## 5. Discussion

Malaysia is a rapidly developing nation within a growing industrial setting. The energy needs have been projected to increase although there are also efforts to reduce the nation's energy intensity through the country's Economic Transformation Plan (ETP). Throughout its journey towards modernization and industrialization, the country has continuously enjoyed a stable, reliable electricity supply at relatively low prices. The threat of climate change would bring change upon this scenario. The support and participation towards GHG emission reductions would be required from all nations. Malaysia is fast becoming an industrialized nation and therefore, has a greater role in the fight against climate change. CCS in its current form is expensive and in the future after considering all the possible cost improvement would still be more expensive than the current conventional fossil fuel based energy. This is a hard fact which is difficult to be accepted by many. The legislator, the industries and the general public must be prepared to adapt to a costlier energy scenario if there is to be any real progress towards climate change mitigation.

When Malaysia commits towards emission targets as per the current developed nations in the Kyoto Protocol, policy makers would be called upon to enact and roll out a national carbon emissions mitigation plan. The plan may include measures that would reduce the emissions from the electricity sector. There are a number of options available for the reduction of $CO_2$ emissions while supporting the demand for electricity to power the nation's growing economy. CCS would be an attractive technology that can complement current existing and planned emission reduction measures. However, the concern on the technical reliability and

safety, implementation cost and availability of quality storage capacity must first be addressed.

On the surface, efforts to mitigate climate change including CCS might look expensive. Nonetheless, with the onset of climate change, much more mitigation efforts are required in order to help avoid costly future devastation [5,80].

## 6. Conclusion

In this paper, we have investigated the feasibility of CCS as a carbon emissions mitigation technology for Malaysia. From our assessment framework, it was shown that the practicality of CCS for Malaysia will depend on a few key criteria, namely the climate change policies on the international and local front, the maturity of the technology, the economic competitiveness of the technology, the speed in which the technology can become available and also the availability of quality storage capacity. It has been noted that there must be appropriate climate policies to govern and motivate the control of GHG emissions (see [81–83]). In this initial assessment, it was determined that certain variants of CCS capture have a lot of potential for wide scale deployment and the large scale demonstration projects would provide much needed certainty on the maturity of the technology. Cost wise, CCS technology is still more costly if compared to current electricity generation practices, which freely emit carbon dioxide into the atmosphere. Then again, the cost of CCS remains comparable to other available GHG mitigation technologies currently available [84]. The availability of quality storage capacity would be a limiting factor for the mitigation of $CO_2$ emissions through CCS, although some studies believe that there is an excess of geologic storage capacity for mitigation purposes [85].

The answer to the question of climate change prevention does not lie in any single technology or approach. There appears to be a strong case for CCS to contribute towards a portfolio of options for climate change mitigation. However, other pressing factors, including the need for a reliable and dependable energy supply and security must also be addressed when seeking an amicable solution towards the challenge. CCS provides the benefit of continued exploitation of fossil energy source while providing a solution towards containing carbon emissions. It can be considered as an insurance policy towards the risk of climate change and serves as a bridge towards sustainable energy sources of the future.

Thus, CCS has the potential to become an important $CO_2$ emission mitigation technology in Malaysia, particularly if the technology is matured for deployment, the cost is competitive and there is available storage capacity.

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